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V-BAND TRAVELING-WAVE TUBE  
SLOW-WAVE CIRCUIT DESIGN (NASA.  
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# Novel High-Gain, Improved-Bandwidth, Finned-Ladder V-Band Traveling-Wave Tube Slow-Wave Circuit Design

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ORIGINAL CONTENT

COLOR ILLUSTRATIONS

**Abstract**—The V-band frequency range of 59–64 GHz is a region of the millimeter-wave spectrum that has been designated for inter-satellite communications. As a first effort to develop a high-efficiency V-band Traveling-Wave Tube (TWT), variations on a ring-plane slow-wave circuit were computationally investigated to develop an alternative to the more conventional ferruled coupled-cavity circuit. The ring-plane circuit was chosen because of its high interaction impedance, large beam aperture, and excellent thermal dissipation properties. Despite these advantages, however, low bandwidth and high voltage requirements have, until now, prevented its acceptance outside the laboratory.

In this paper, the three-dimensional electrodynamic simulation code MAFIA (Solution of MAxwell's Equations by the FInite-Integration-Algorithm) is used to investigate methods of increasing the bandwidth and lowering the operating voltage of the ring-plane circuit. Calculations of frequency-phase dispersion, beam on-axis interaction impedance, attenuation, and small-signal gain per wavelength were performed for various geometric variations and loading distributions of the ring-plane TWT slow-wave circuit. Based on the results of the variations, a circuit termed the finned-ladder TWT slow-wave circuit was designed and is compared here to the scaled prototype ring-plane and a conventional ferruled coupled-cavity TWT circuit over the V-band frequency range. The simulation results indicate that this circuit has a much higher gain, significantly wider bandwidth, and a much lower voltage requirement than the scaled ring-plane prototype circuit, while retaining its excellent thermal dissipation properties. The finned-ladder circuit has a much larger small-signal gain per wavelength than the ferruled coupled-cavity circuit, but with a moderate sacrifice in bandwidth.

## NOMENCLATURE

$A_1$	Initial loss factor, in dB.
$A_2$	Space-charge loss factor, in dB.
$B$	$54.6 X_1$ .
$BC$	Small-signal gain per number of electronic wavelengths on the circuit, in dB.
$C$	Pierce's gain parameter.

$E_n$	On-axis axial electric field magnitude for the $n$ th space harmonic component of a traveling wave, in volts per meter.
$G$	Small-signal gain, in dB.
$I_o$	Beam current, in amperes.
$K_n$	Beam on-axis interaction impedance for $n$ th space harmonic, in Ohms.
$K_{avgn}$	Beam interaction impedance averaged over the beam area for $n$ th space harmonic, in Ohms.
$L$	Cavity length, in meters.
$N$	Number of electronic wavelengths on the circuit.
$P_{RF}$	RF power flow, in watts.
$P_L$	RF power loss per unit length, in watts per meter.
$v_g$	Group velocity, in meters per second.
$V_o$	Beam voltage, in volts.
$W$	Stored electromagnetic energy per unit length, in joules per meter.
$X_1$	Real part of the incremental propagation constant of the growing wave.
$\alpha$	Attenuation, in dB per cavity.
$\beta_n$	Axial phase constant for $n$ th space harmonic, in radians per meter.

## I. INTRODUCTION

THE ring-plane is a potential Traveling-Wave Tube (TWT) slow-wave circuit for use in high-power applications at millimeter-wave frequencies. Advantageous characteristics that enable high-power operation with this fundamental forward wave circuit include large interaction impedance, large beam aperture, and excellent thermal dissipation properties. A prototype ring-plane TWT slow-wave circuit is shown in Fig. 1. The circuit of [1] was constructed from a single piece of molybdenum and consists of a series of rings supported by two planes and encased in an outer cylindrical barrel. With a 98-kV, 3.7-Amp electron beam, this circuit produced 43-kW peak power at 33 GHz.

Disadvantages of low bandwidth and high voltage requirements have discouraged acceptance of the ring-plane TWT outside the laboratory. In an effort to alleviate these disadvantages, the three-dimensional simulation code MAFIA (Solution of MAxwell's Equations by the FInite-Integration-Algorithm) was used to calculate the dispersion, beam on-axis interaction impedance, and attenuation for the prototype ring-plane circuit

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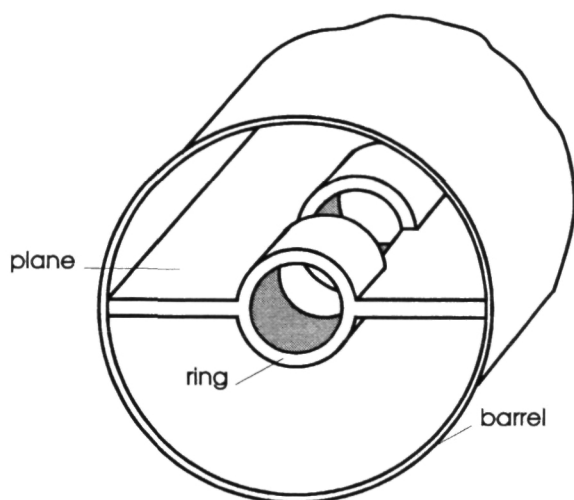


Fig. 1. Ring-plane prototype TWT slow-wave circuit.

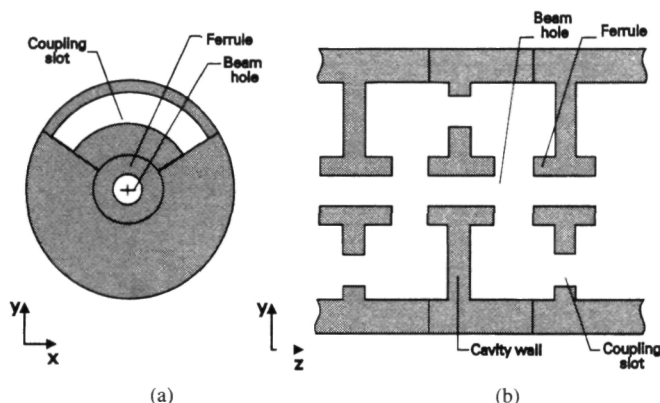


Fig. 2. Ferruled coupled-cavity TWT slow-wave circuit. (a) End view. (b) Top view.

scaled to V-band and several variations of the ring-plane circuit. Using these simulated cold-test results, the small-signal gain per electronic wavelength of each circuit was calculated to determine the effects of the variations on gain and bandwidth. These results were used to design the novel finned-ladder TWT slow-wave circuit, a high-gain and improved-bandwidth circuit, which is compared across the V-band frequency range with the ring-plane prototype circuit of [2] and the Hughes model 961HA ferruled coupled-cavity circuit of [3].

The Hughes model 961HA ferruled coupled-cavity TWT was developed under NASA Contract NAS3-25090 [3]. It produces 60 watts minimum and 70 watts average CW output power across the V-band frequency range. With a 4-stage depressed collector, the 961HA operates with an average overall efficiency of 28%. The conventional ferruled coupled-cavity circuit is shown schematically in Fig. 2(a) and (b) for the end and top views, respectively.

MAFIA is a powerful, three-dimensional, electrodynamic code written in FORTRAN 77 that is used for the computer-aided design of 2-D and fully 3-D electromagnetic devices such as magnets, RF cavities, waveguides, antennas, etc. The Finite Integration Technique (FIT) algorithm produces a set of

finite-difference matrix equations for the electric and magnetic field vectors in the structure under study. The solution of these equations yields static, frequency-domain, or time-domain solutions of Maxwell's equations [4], [5]. The code includes nine interrelated modules. The cold-test characteristics of this report were calculated using the *M* (mesh generator), *E* (eigenmode solver), and *P* (postprocessor) modules of MAFIA. The remaining modules include a static solver, 2-D and 3-D time domain solvers, 2-D and 3-D particle-in-cell codes, and a frequency-domain eddy-current solver. The success of using MAFIA to obtain accurate cold-test results, as compared to experiment for the Hughes 961HA ferruled coupled-cavity and the Varian TunneLadder TWT slow-wave circuits, has been demonstrated in [6].

## II. ANALYSIS

The MAFIA mesh used for the scaled prototype ring-plane calculations is shown for the end view in Fig. 3. The frequency-phase dispersion characteristics were obtained by using the quasi-periodic boundary condition of MAFIA. This feature of the code allows the user to choose a fixed phase advance per cavity in the axial direction. Because resonant frequencies will be calculated for each assigned value of phase advance, an exceptionally accurate dispersion curve can be formed. This is critical in calculating the group velocity with dependable precision.

The beam on-axis interaction impedance is a measure of the strength of interaction between an RF wave space harmonic and the electron beam [7]. In the ring-plane slow-wave circuit, the beam is synchronous with only the fundamental RF space harmonic. For this space harmonic, the beam interaction impedance on the axis is defined as

$$K_0 = \frac{E_0^2}{2\beta_0^2 P_{RF}} \quad (1)$$

where  $E_0$  is the magnitude of the fundamental space harmonic of the on-axis electric field,  $\beta_0$  is the axial phase constant, and  $P_{RF}$  is the RF power flow defined by

$$P_{RF} = W v_g \quad (2)$$

where  $v_g$  is the group velocity, and  $W$  is the stored electromagnetic energy per unit length.

The method for calculating the beam on-axis interaction impedance with MAFIA is similar to experimental methods where  $\omega$ - $\beta$  characteristics are determined by measuring the resonant frequencies in a section of circuit shorted at both ends. Truncating an infinite circuit at two points with either an electric or magnetic wall with MAFIA corresponds to simulating standing waves with an integral number of half-wavelengths (phase shifts of  $\pi$ ) within the isolated circuit section.

The attenuation in dB/cavity can be expressed as

$$\alpha = 8.686 \frac{P_L L}{2W v_g} \quad (3)$$

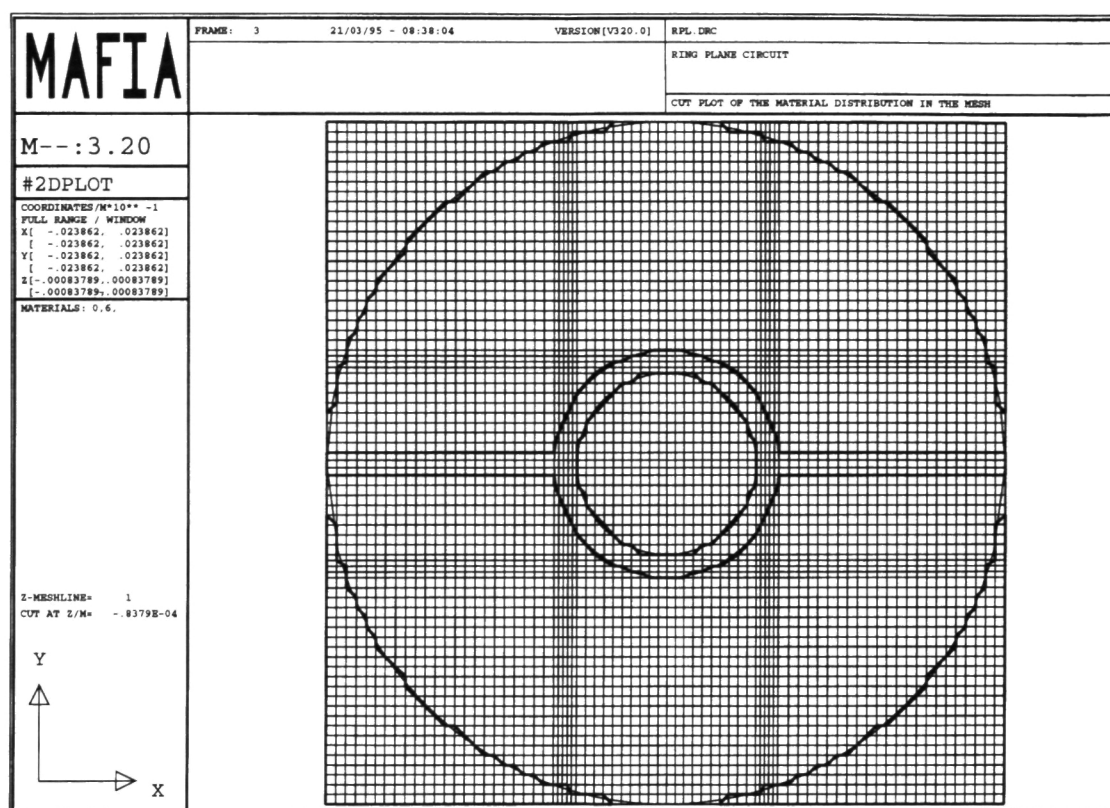


Fig. 3. MAFIA grid for end view of ring-plane prototype TWT slow-wave circuit.

where  $P_L$  is the total power loss per unit length and  $L$  is the cavity length [8]. The necessary input for the attenuation calculations includes specifying a conductivity value for conducting materials. An effective conductivity value is used, acquired by matching simulated results to experimental results for a ferruled coupled-cavity TWT slow-wave circuit [5].

The small-signal gain calculations were calculated from the relationship  $G = A_1 + A_2 + BCN$  where  $A_1$  is the initial loss of the circuit,  $A_2$  is the space-charge loss, and  $B = 54.6X_1$  where  $X_1$  is the real part of the incremental propagation constant of the growing wave and  $N$  is the number of electronic wavelengths on the circuit [7]. For a beam with constant current density, Pierce's gain parameter  $C$  is defined as

$$C^3 = \frac{K_{avgn} I_o}{4V_o} \quad (4)$$

where  $K_{avgn}$  is the beam interaction impedance of the  $n$ th space harmonic averaged over the beam area,  $I_o$  is the beam current, and  $V_o$  is the beam voltage.

### III. RING-PLANE PROTOTYPE VARIATIONS

The finned-ladder slow-wave circuit was developed from the results of several simulated variations of the scaled prototype ring-plane circuit. The modifications made to the ring-plane circuit include an enlarged outer barrel diameter, slots introduced in the support planes, and metal fins included as a loading method.

This study focuses on a circuit design in the V-band frequency range of the millimeter-wave spectrum that has been designated for inter-satellite communications where large bandwidth, high efficiency, and modest weight are important. The scaled prototype ring-plane circuit has a small bandwidth and operates at an extremely high voltage, thus requiring a large power supply. In order to decrease the operating voltage by decreasing the phase velocity of the circuit, the outer cylindrical barrel diameter was enlarged (see Fig. 1). Existence of a barrel around the circuit provides the low frequency cutoff point, so, by increasing the barrel diameter from the prototype dimension, an accompanying decrease in this lower cutoff frequency occurs without a significant effect on the upper cutoff, thus increasing the cold bandwidth of the circuit. This is explained by the high concentration of the electric field between the rings of the circuit at high frequencies versus a field distributed more throughout the region between the rings and the barrel at low frequencies. The enlarged barrel variation, therefore, will have greater effects on the field pattern at lower frequencies, thereby selectively altering the lower cutoff. Limitations inherent to focusing considerations are placed on the barrel diameter variations. As the barrel is placed farther away from the circuit, problems may arise with the weight of necessarily stronger focusing magnets.

To further widen the bandwidth of the circuit and reduce the operating voltage, common loading schemes were investigated. Because manufacturing and thermal considerations are less complicated with an all-metal construction, dielectric loading methods to slow the circuit were not investigated. By



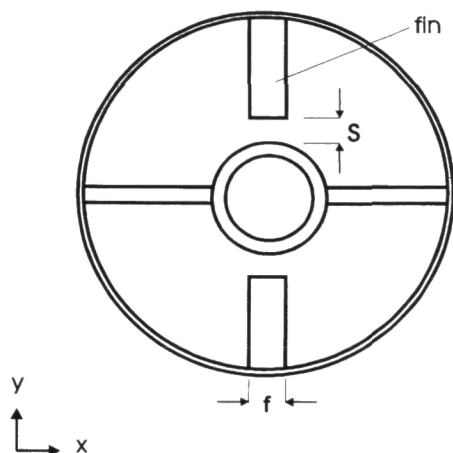


Fig. 4. Ring-plane TWT slow-wave circuit with loading fins.

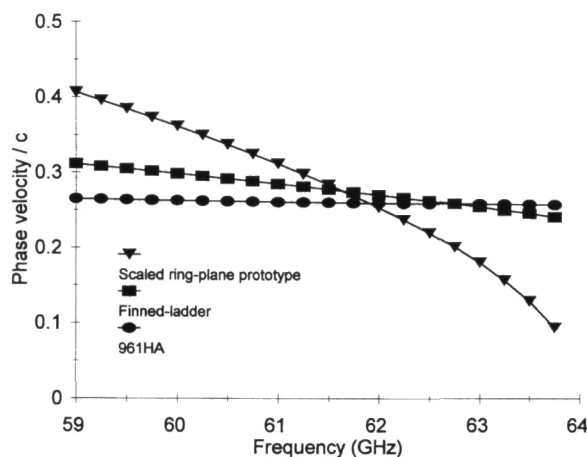


Fig. 5. Normalized phase-velocity.

adding metal fins with width  $f$  to the outer barrel, as shown in Fig. 4, the fields are perturbed more at lower frequencies than at higher values (as mentioned above), allowing for control of the dispersion. The loading fins and barrel increase did have a large effect on the reduction of operating voltage and increase in cold circuit bandwidth, as is apparent in Fig. 5. The distance between the ring and fin,  $s$ , was made as small as possible (taking manufacturing issues into consideration), as this dimension provided the maximum effect on slowing circuit phase velocity and broadening bandwidth. It is worth noting that, if the circuit dimensions are scaled for lower frequency operation, this distance  $s$  could be decreased for further improvement in the bandwidth.

Unfortunately, both the barrel enlargement and fin loading caused a corresponding reduction in the beam on-axis interaction impedance. To counteract for this decrease in impedance, slots with length  $L$  were added to the support planes (see Fig. 6). The support planes of the ring-plane circuit cause the electric field between rings to go to zero azimuthally at the supports. These regions of zero field cause a corresponding decrease in the axial electric field, thus decreasing the beam on-axis interaction impedance. By slotting the support planes,

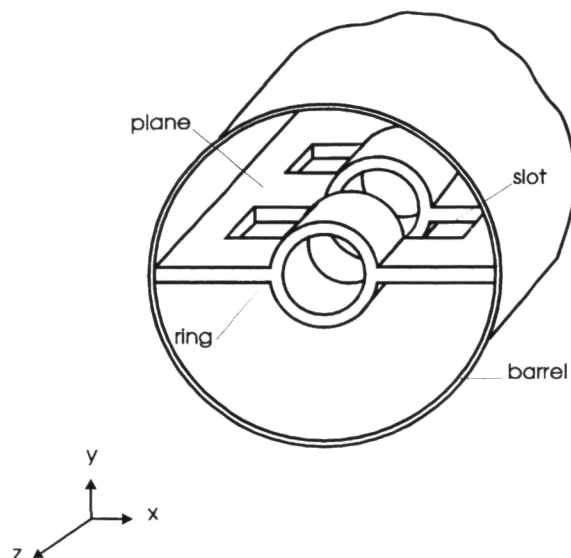


Fig. 6. Ring-plane TWT slow-wave circuit with slotted support planes.

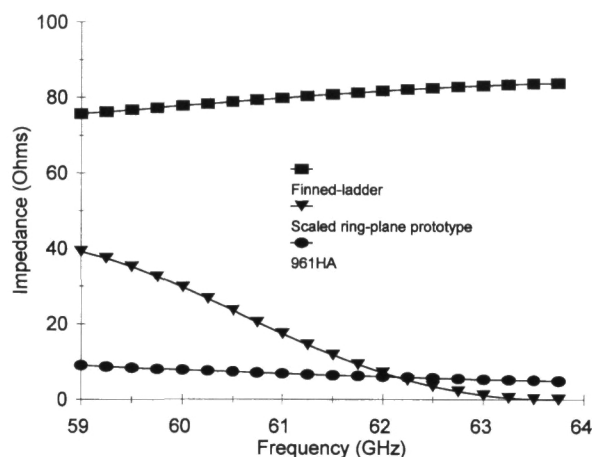


Fig. 7. Simulated beam on-axis interaction impedance.

the zero field condition is removed, permitting a larger axial electric field to exist. This results in a significant increase in the impedance, as shown in Fig. 7.

Fig. 8 shows a MAFIA three-dimensional view of the circuit termed the finned-ladder circuit with the modifications described above. Fig. 9 shows a MAFIA three-dimensional electric field plot of a zoomed in portion of the finned-ladder circuit at a phase shift per cavity of 45 degrees, where the arrow size is proportional in size to the magnitude of the field. The high concentration of the electric field between the rings at a low frequency is illustrated here. Fig. 10 shows another MAFIA plot which contours the losses of the circuit, the highest loss represented by red. From this figure, it can be seen that the highest concentration of losses is in the slots.

#### IV. SIMULATION RESULTS

In order to compare the ring-plane prototype and finned-ladder circuits to the conventional ferruled coupled-cavity

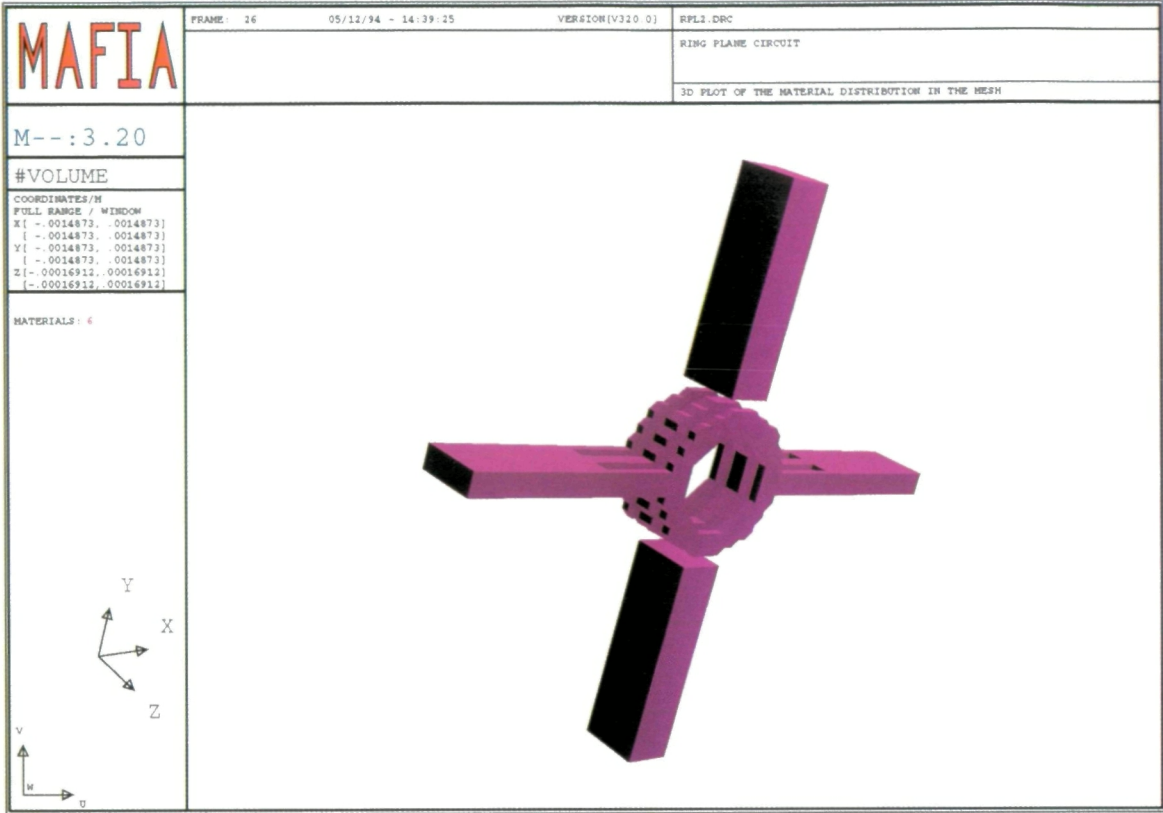


Fig. 8. MAFIA three-dimensional view of finned-ladder TWT slow-wave circuit.

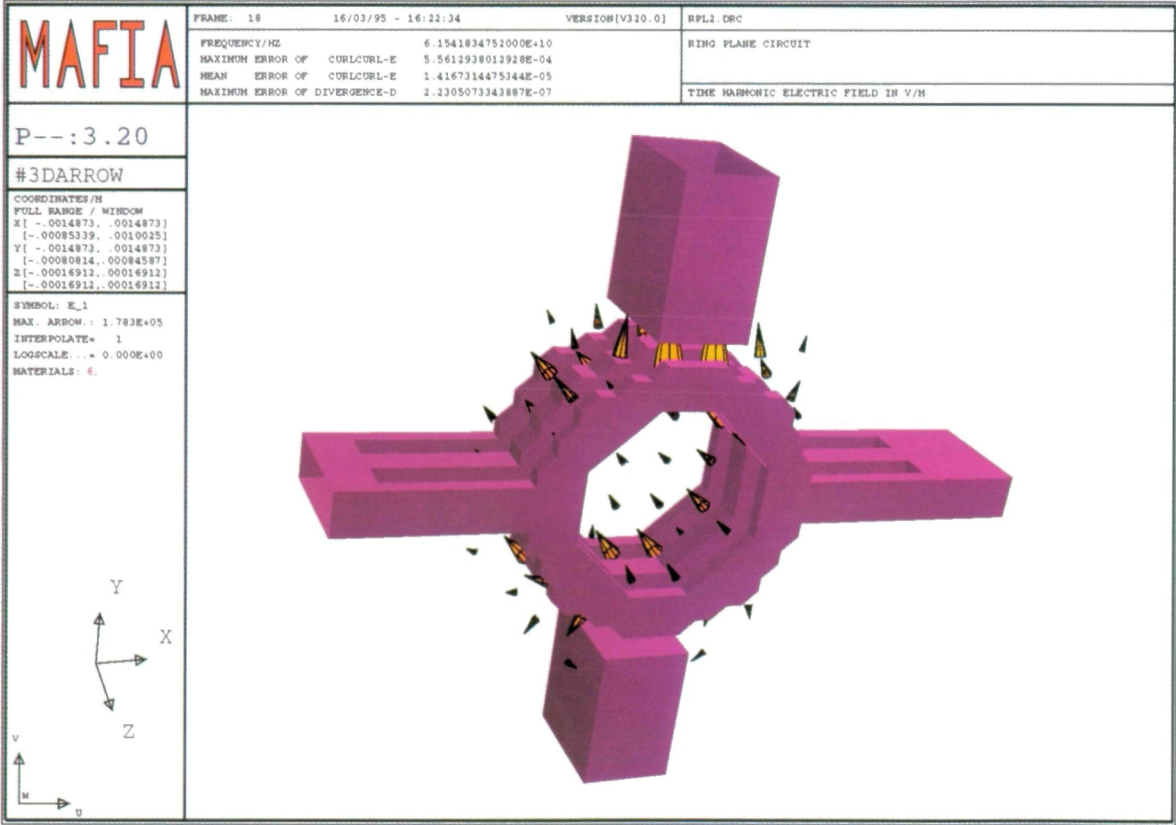


Fig. 9. MAFIA three-dimensional view of the electric field pattern at  $\beta L = 45$  degrees for a zoomed in portion of the finned-ladder circuit.

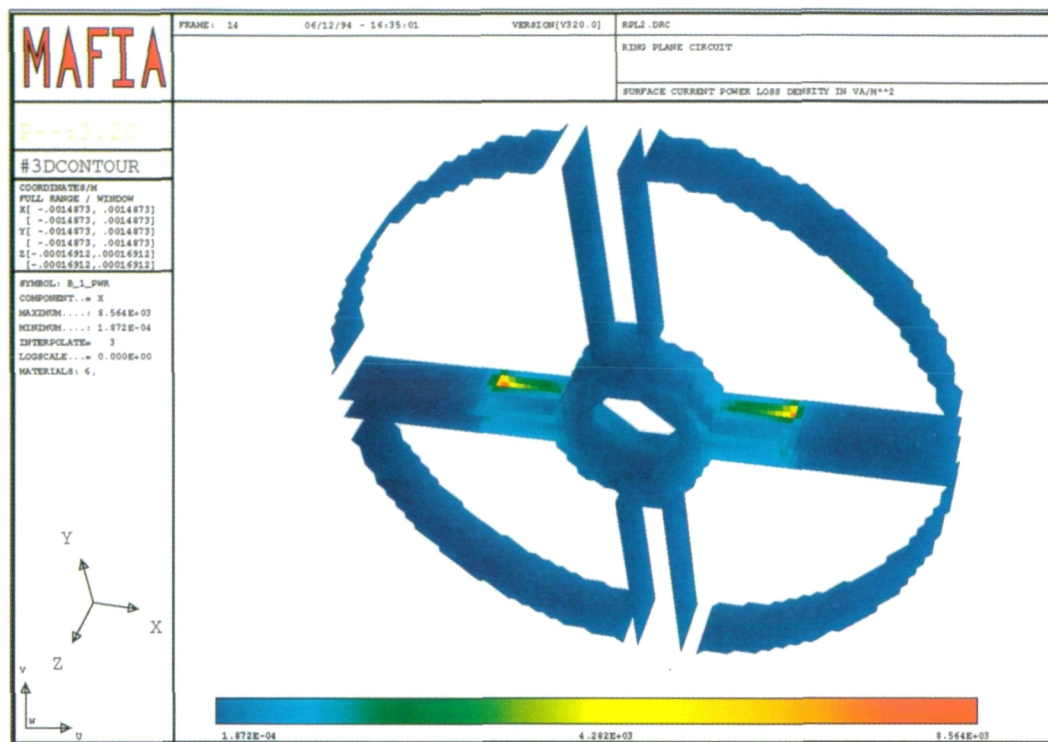


Fig. 10. MAFIA three-dimensional contour plot of losses for finned-ladder circuit.

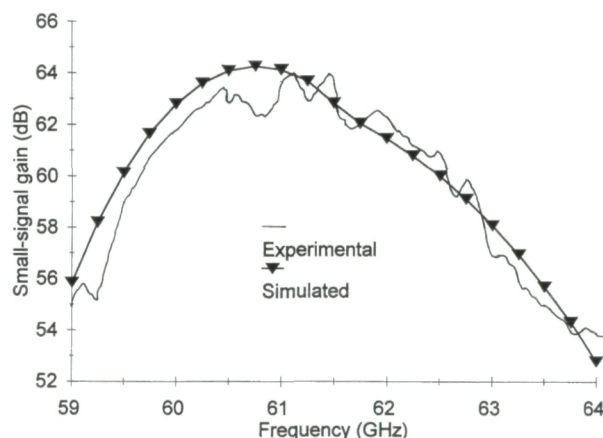


Fig. 11. 961HA experimental small-signal gain compared to computed small-signal gain using MAFIA cold-test results.

TABLE I  
MAJOR DESIGN PARAMETERS AT MIDBAND

Operating Frequency	61.5 GHz
Beam Voltage	20 kV
Beam Current	74 mA
Beam radius/aperture radius	0.5

total circuit length of each TWT is undetermined, the small-signal gain per number of electronic wavelengths BC is compared for each case in Fig. 12. This plot shows that the finned-ladder circuit far exceeds the gain per number of electronic wavelengths and the bandwidth of the scaled ring-plane prototype circuit. Compared to the 961HA, the midband gain is far superior, with a moderate sacrifice in bandwidth.

## V. SUMMARY

circuit, computations involving the combined use of three-dimensional and small-signal simulation codes were performed. The three-dimensional simulation code MAFIA was used to model the cavity designs and to accurately simulate the cold-test parameters (dispersion, impedance, and attenuation). From the computed cold-test parameters, the small-signal gain is determined as a function of frequency. Fig. 11 compares the simulated small-signal gain to experiment for the 961HA. The agreement is excellent, indicating that the calculations are accurate for the 961HA ferruled coupled-cavity TWT.

To establish a meaningful comparison of the scaled ring-plane prototype and novel finned-ladder TWT's with the conventional ferruled coupled-cavity TWT, the ring-plane and finned-ladder circuits were designed with the same operating parameters as the 961HA listed in Table I. Because the

The value of computer modeling in TWT development was demonstrated in the presentation of a novel high gain, improved-bandwidth, finned-ladder TWT slow-wave circuit. This circuit shows a major improvement in beam interaction impedance, gain, and bandwidth, and a significantly reduced operating voltage, compared to the scaled ring-plane prototype TWT, while retaining excellent thermal dissipation properties. Compared to the conventional coupled-cavity TWT, the finned-ladder TWT with similar design parameters shows a superior midband gain without a large sacrifice in bandwidth.

Further computational work is needed to investigate stability and manufacturing tolerances. It is expected that the time-dependent module of MAFIA can be used to design termination and output matches. A detailed circuit design will

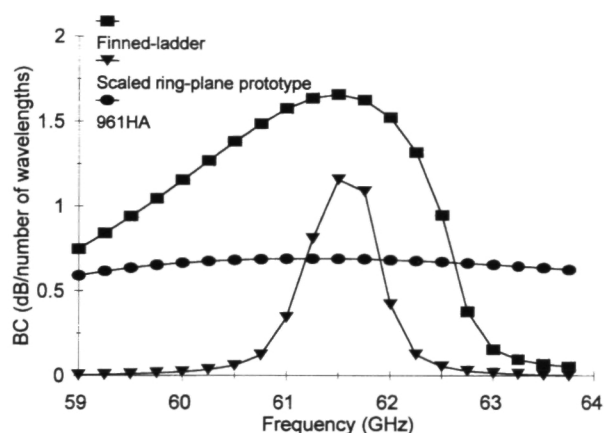


Fig. 12. Simulated small-signal gain per number of electronic wavelengths.

also require modeling the circuit with a large-signal coupled-cavity TWT computer code [9].

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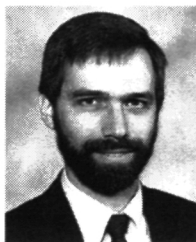
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From 1991 to 1992, she was with NASA Lewis Research Center, Cleveland, OH as an intern student, where her work involved analyzing the TunnelLadder traveling-wave tube (TWT) slow-wave circuit using Micro-SOS, a 3-D PIC code. Upon graduation from the University of Dayton, she became a full-time employee of the ANALEX Corporation, working with the same staff at NASA Lewis Research Center. Currently, she is using the 3-D PIC computer code, MAFIA. Her research interests have involved the computational modeling and design of TWT components and electro- and magneto-static focusing systems used in field emission microscopes. She is also involved in the automation of a traveling-wave tube test station.

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